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Transverse Electric Propagation of a Two-Dimensional Wave Traveling in a Gas Turbine Engine

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Abstract

Two-dimensional transverse electric (TE) electromagnetic scattering of a sine source disturbance was numerically solved using the finite difference-time domain (FD-TD) method with the inclusion of the Mur absorbing boundary conditions. The imposition of the appropriate boundary conditions appears to be effective for absorption of dispersive, multimodal, and even evanescent energy. The absorption as used in this study is thought at best to be in order of the analytical absorbing boundary condition because of increasing reflection at oblique incident angles. The solution presented demonstrates the efficient use of the second approximation of the Mur boundary condition since the mesh was simple, incorporation of the TE equations quite straightforward, and application of the boundary stipulations continuously dependent upon the data. This method development and subsequent solution does show that a radiative point source in a two-dimensional mesh can simulate an electromagnetic disturbance occurring from a region in a gas turbine engine, along with its attendant wave distribution and pattern with intensity magnitudes that help demonstrate how an excitation can possibly affect an electromagnetic device in its operational voltage surges.

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1. INTRODUCTION

Many authors such as Taylor (1969), Taflove and Brodwin (1975), Taflove (1980), Merewether (1971), and Kunz and Lee (1978) have proposed methods for absorbing boundary conditions for a two-dimensional (2-D) transverse magnetic wave. Solutions to the time-dependent Maxwell's equations in general form are starting to gain familiarity due to the relatively inexpensive processing times and capacities of modern-day machines. Numerical solutions to a scattering phenomenon for which the ratio of the characteristic linear dimension of the obstacle to the wavelength are now within the forefront of state-of-the-art architecture and technology. However, the difficulty still lies in the imposition of the boundary conditions for 2-D as well as three-dimensional (3-D) problems. For the transient transverse magnetic traveling wave, Korjack (1997,1995) has shown that in the case of two dimensions, numerical solutions are practical even when the characteristic length of the obstacle is moderately large compared to that of an incoming wave. Two-dimensional electromagnetic wave propagation equations are either transverse magnetic or transverse electric(TE) in nature. Since the very essence of understanding the electric wave equations is to solve only the TE case, it behooves us to investigate these equations as applied to our study of wave propagations that occur in a gas turbine which excite electrical components in such a way as to produce a voltage spike in one of the components and cause a failure. Hence, it is necessary to explore the solution of the Maxwell equations for the 2-D, TE situation especially since physical insight can be gained by their solutions in telling us the magnitude of these waves and their respective traveling rates of intensity.

In this report, the TE equations will be solved using boundary conditions based upon Engquist and Majda (1977) and Mur (1981), to simulate a 2-D transient TE distribution of primary electric and secondary magnetic field intensities for a sinusoidal wave originating and generated from the center and emanating in an omnidirectional manner. This treatise is a result of work done over the past year reflecting a completely different set of constitutive equations dealing with TE approach; it was previously demonstrated how transverse magnetic electromagnetic waves propagate and distribute themselves in a 2-D mesh network, emanating from a source of electromagnetic disturbance as typified in one of the gas turbine engine components. This study will complement

an earlier work by Korjack (1997) to look at the electromagnetic interference (EMI) produced by a starter, causing the analog electronic control unit diagnostic connector to abort the actual start of the engine; both wave phenomena, (i.e., electric and magnetic) will help explain the intensities of the disturbances over time and at what topology so that electrical component signature can be possibly compared to excitation signature for resonance asscociation.

The finite-difference time domain method is a direct solution of the Maxwell time dependent curl equations. It employs no potentials at all, but instead applies simple, second or fourth order accurate difference approximations for the space and time derivatives of the electric and magnetic fields directly to the respective differential operators of the curl expressions. This achieves a sampled data reduction of the continuous electromagnetic field in a volume of space over a period of time. Space and time discretizations are selected to bound errors in the sampling process and to ensure numerical stability of the algorithm. Electric and magnetic field components are interleaved in space to permit a natural satisfaction of tangential field continuity conditions at media interfaces. The resulting system of equations for the field is then fully explicit so that there is no need to solve a set of linear equations, and the required computer storage and running time is proportional to the electrical size of the space modeled. Hence, this method is no more than a time-marching procedure resulting in a simulation of continuous actual waves by numerical analogs propagating in a data space stored in a computer.

2. MATHEMATICAL AND NUMERICAL REVIEW

The TE mode sets up electric field lines in a plane perpendicular to the long axis of the 2-D structure. Clearly, these lines can be orthogonal to the structure surface, and if the structure is metallic, as is the case in the gas turbine engine immediately adjacent to the starter components, substantial electric fields can be supported at the structure surface without violating the boundary condition of zero electric fields tangential to a perfectly conducting surface, (e.g., the engine wall, per se). As a result, the TE mode can support propagating electromagnetic fields bound closely together or guided by the surface of a metal structure such as in a creeping wave that might travel from an eddy current loss to a switch, such as in the starter itself. Hence, let us formulate this 2-D

model via a transverse transient electric technique so as to simulate the electrical intensities and their respective propagation throughout a simplified rectangular mesh.

2.1 Governing Equations. The Maxwell's equations governing the propagation of electromagnetic waves in an isotropic, homogeneous medium are:

$$\frac{\partial \vec{H}}{\partial t} = -\frac{1}{\mu} \nabla \times \vec{E} - \frac{\rho}{\mu} \vec{H} \tag{1}$$

$$\frac{\partial \vec{E}}{\partial t} = \frac{1}{\epsilon} [\nabla \times \vec{H} - \sigma \vec{E}], \tag{2}$$

where μ, ϵ, and σ are the permeability of space, the permittivity of space and conductivity respectively, and ρ is the magnetic resistivity that will be neglected in this case noted that μ, ϵ, and σ will be considered constant in this analysis.

For the TE case in a 2-D rectangular (x,y) coordinate system, equations 1 and 2 simply become

$$-\mu \frac{\partial H_z}{\partial t} = \frac{\partial E_y}{\partial x} - \frac{\partial E_y}{\partial y} \tag{3}$$

$$\frac{1}{\varepsilon} \frac{\partial H_z}{\partial y} = \frac{\partial E_x}{\partial t} \tag{4}$$

$$-\frac{\partial H_z}{\partial x} = \frac{1}{\varepsilon} \frac{\partial E_y}{\partial t}, \tag{5}$$

where H is the magnetic field intensity and E is the electric field intensity. Let us also assume that we are dealing with a lossless-material case that implies directly that $\rho = \sigma = 0$.

2.2 Numerical Stability. The numerical algorithms for Maxwell's curl equations, which are defined by the finite difference equations, require that the time increment, Δt, have a specific bound relative to the lattice space increments, viz., Δx and Δy. This bound is necessary to avoid numerical instability, which is an undesirable possibility with explicit differential equation solvers that can cause the computed results to spuriously increase without limit as time marching continues. Hence, the Courant stability condition must be satisfied as demonstrated by Yee (1966).

2.3 Boundary Conditions. The common initial and boundary values of the transverse electrical propagation reside on the interface of two different media. If we assume that perfect electrical conductivity exists, then the appropriate boundary conditions at the surfaces are commonly given by Harrington (1961) and Stratton (1941). The finite-difference approximation of the absorbing boundary conditions were presented by Korjack (1997). These approximations have a local truncation error of the second order in all increments. The absorbing boundary conditions for the H-field components are tangential to the boundary of interest. The discretized form of the boundary condition for H_z at this boundary were simulated as done by Mur (1981). The finite-difference approximation was derived using centered differences having local truncation errors of the second order in all increments in both the space and the time increments.

2.4 Sinusoidal Disturbance. The sinusoidal external excitation used in this analysis was the approximate type of pulse used by Korjack (1997). This disturbance propagates in the +z direction and has the representation of

$$J_z = \sin(2\pi f t), \tag{6}$$

where

$$f = 1/(50 \cdot dt). \tag{7}$$

This type of excitation is considered a soft source, which results from Taflove's work in realizing a compact wave source for use in simulations of sinusoidal steady-state illumination, (Taflove (1975)). In fact, the virtual current soft source was the first compact wave source that succeeded in permitting reflected numerical wave energy to pass through the source without hindrance or retro-reflection, thereby permitting an unlimited number of steps to be run if desired. This source is based upon a slight manipulation of Maxwell's second equation, viz., equation (2), but where the presence of an electric current source such as J_z is allowed.

3. SUMMARY/RESULTS

Two-dimensional (TE) electromagnetic scattering of a sine source disturbance was numerically solved using the finite difference-time domain(FD-TD) method with the inclusion of the Mur absorbing boundary conditions. Figures 1 and 2 depict the z component of the magnetic field intensity distribution with respect to the x and y planes at 50 and 75 time steps of the disturbance development, respectively. Each time step represents a multiple of $1.0 \cdot 10^{-12}$ s. Figures 3 and 4 depict the z component of the magnetic field intensity distribution with respect to the x and y planes at 100 and 150 time steps of the disturbance development, respectively, which illustrate the source disturbances growth from center excitation to the outer boundaries of the 2-D mesh. The imposition of the appropriate boundary conditions appears to be effective for absorption of dispersive, multimodal, and even evanescent energy. The ideal boundary condition would provide for reflectionless transmission of a plane wave that propagates normally across the interface between free space and the outer boundary layer; layers of this type have been used in the past to terminate FD-TD grids but with gross distortions at or near all points of discontinuity. However, the absorption as used in this study is thought at best to be in order of the analytical absorbing boundary condition because of increasing reflection at oblique incident angles.

The solution presented here demonstrates the efficient use of the second approximation of the Mur boundary condition since the mesh was simple, incorporation of the TE equations quite straightforward, the application of the boundary stipulations continuously dependent upon the data and rapid computations on a C90 machine as is usual in most well-posed problems. With the second approximation of Mur utilized, an almost circular pattern was obtained on a contour plot (not shown) with only slight deformations at points near the boundaries and far away from the source. Errors that occurred in the mesh were probably caused by grazing incidence waves not well absorbed or partly reflected. Furthermore, note that errors could result by waves exhibiting grazing incidences on a boundary that will certainly not be absorbed, but instead, partly reflected.

This method development and subsequent solution does show that a radiative point source in a 2-D mesh can simulate an electromagnetic disturbance occurring from a region in a gas turbine engine, along with its attendant wave distribution and pattern with intensity magnitudes that help demonstrate how an excitation can possibly affect an electromagnetic device in its operational voltage surges. In addition, this program can also be extended beyond the 2-D case to the case of 3-D transient electromagnetic propagation from a variety of disturbances and excitation sources at different locations of the mesh.

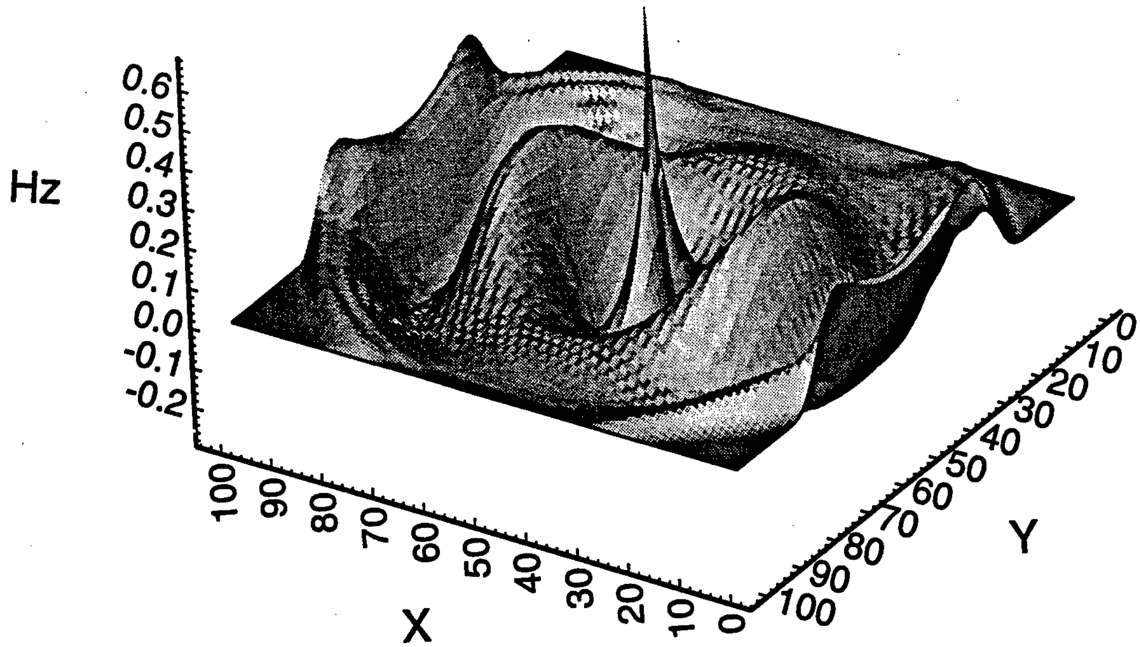

Figure 1. Distribution of the Z-component of magnetic field intensity (V/m) at time step = 50 .

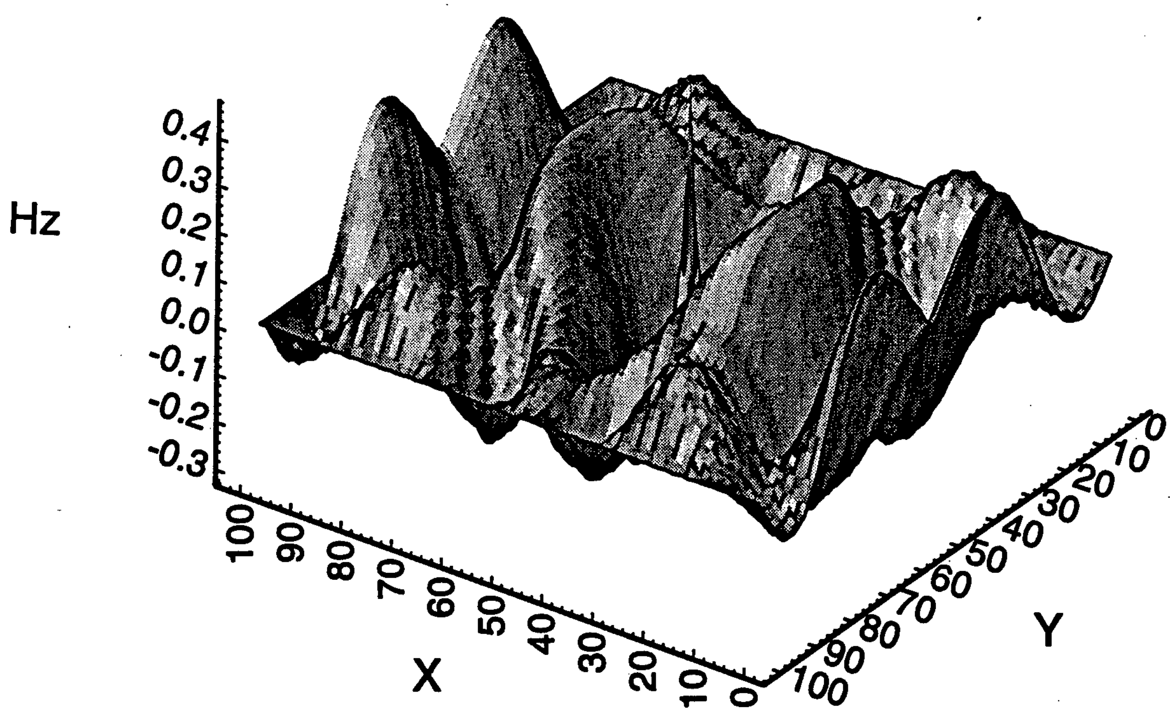

Figure 2. Distribution of the Z-component of magnetic field intensity (V/m) at time step = 75 .

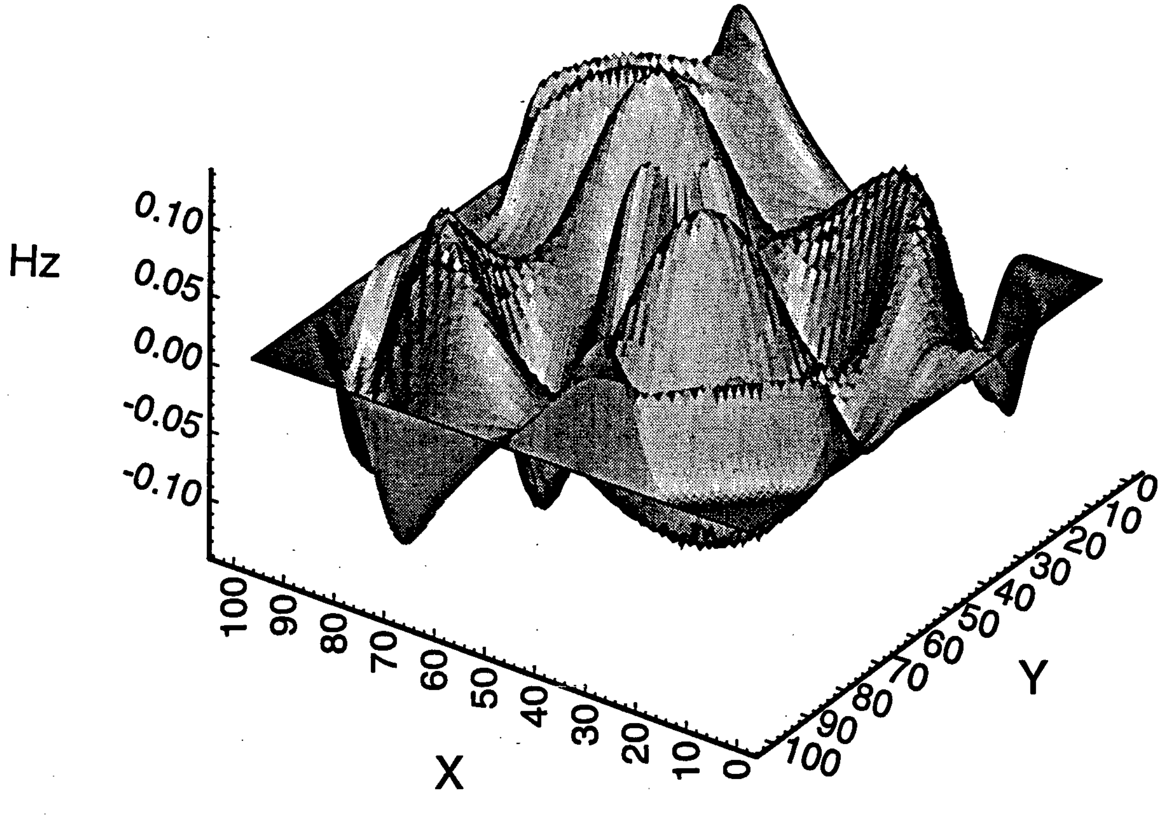

Figure 3. Distribution of the Z-component of magnetic field intensity (V/m) at time step = 100.

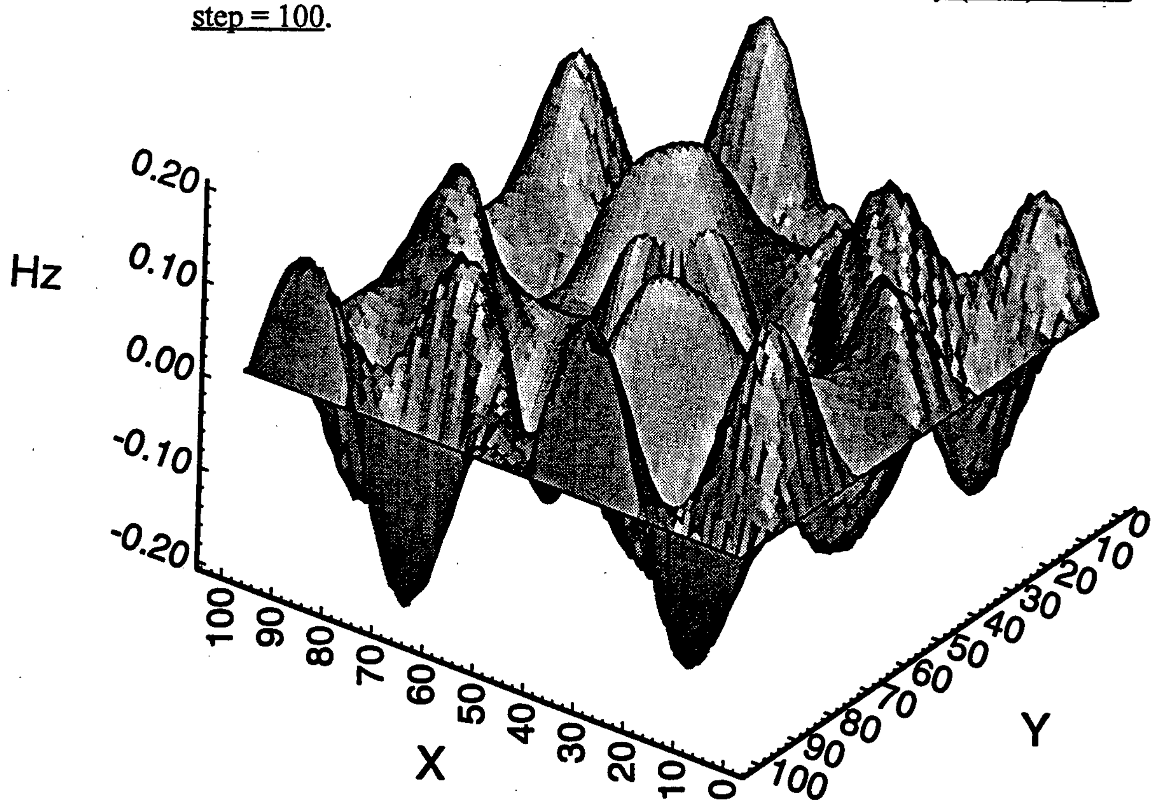

Figure 4. Distribution of the Z-component of magnetic field intensity (V/m) at time step = 150.

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